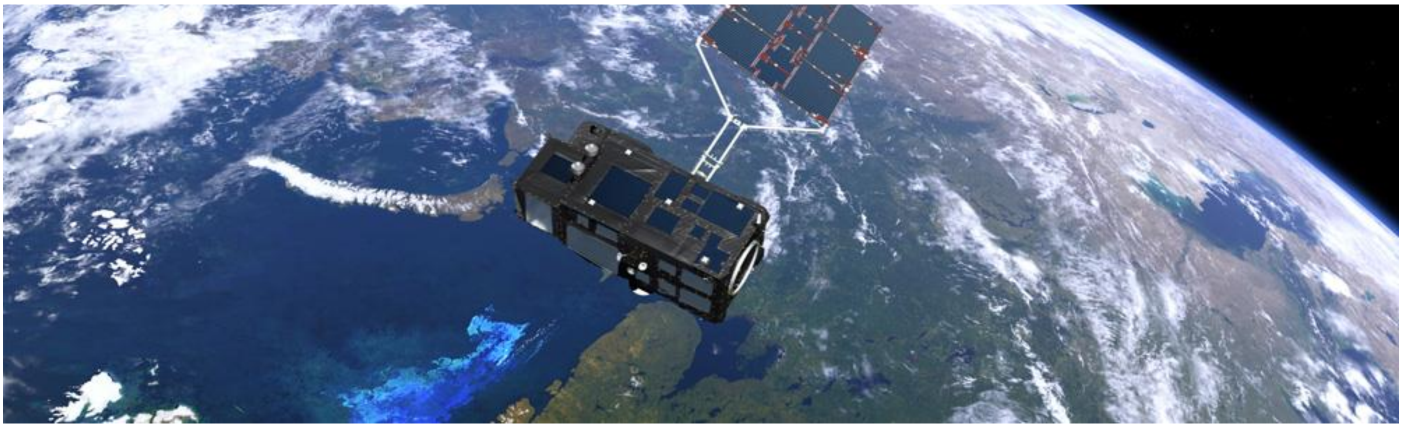
Summary report

EU project Joint Monitoring Programme of the Eutrophication of the North Sea with Satellite data (JMP EUNOSAT)

Part of the JMP EUNOSAT program

May 2019



EUROPEAN COMMISSION
DIRECTORATE-GENERAL
ENVIRONMENT
Directorate D - Water, Marine Environment & Chemicals

Co-funded by the European Union - DG Environment

This report can be cited as:

Enserink, L., Blauw, A., van der Zande, D., Markager S. (2019). **Summary report of the EU project 'Joint monitoring programme of the eutrophication of the North Sea with satellite data' (Ref: DG ENV/MSFD Second Cycle/2016).** 21 pp.

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Financial support:

EU EMFF Programme Implementation of the second cycle of the MSFD – Achieving coherent, coordinated and consistent updates of the determinations of good environment status, initial assessments and environmental targets (DG ENV/MSFD Second Cycle/2016). Grant Agreement No. 11.0661/2017/750678/SUB/ENV.C2

Acknowledgements:

We thank the project partners for providing information and access to their national in-situ data bases and technical support and OSPAR's ICG-Eut and HASEC for their valuable feedback to preliminary results. ESA, NASA, ODESA and CMEMS are acknowledged for the provision of satellite products.

Key words:

Ocean colour, satellite observations, multi-algorithm chlorophyll-a retrieval, North Sea, OSPAR, MSFD, eutrophication, assessment, threshold values, assessment areas, chlorophyll-a, nutrients

The JMP EUNOSAT project partners are: RWS (NL), RBINS (BE), Deltares (NL), AU (DK), Ifremer (FR), PML (UK), MSS (UK), CEFAS (UK), SMHI (SE), IMR (NO), NIVA (NO), UBA (DE), BSH (DE), NLWKN (DE)

1. Summary

The European Marine Strategy Framework Directive (MSFD, EU 2008) requires EU member states to achieve Good Environmental Status (GES) of their seas by 2020. Monitoring and assessment should be performed in a coherent, coordinated and consistent manner in a (sub)region. The North East Atlantic MSFD Region is divided into four sub-regions: the Wider Atlantic, the Bay of Biscay and Iberian Coast, the Celtic Seas and the Greater North Sea. Each member state is required to develop a marine strategy for their marine waters. Therefore, it is important that member states work together to implement each stage of the Directive in a coherent and coordinated way, ensuring comparability across Europe. The OSPAR Convention is a key forum to facilitate many aspects of the coordination process.

The present report is a deliverable of the EU funded project "Joint monitoring programme of the eutrophication of the North Sea with satellite data'. The JMP EUNOSAT consortium included of national institutes responsible for environmental marine monitoring in all North Sea countries. The project contributes to a major challenge in OSPAR, *i.e*. shifting from national eutrophication assessments that are difficult to compare across national borders to a coherent joint assessment for the Quality Status Report 2023, which in turn will provide a common basis for the 2024 reporting under the MSFD.

We present a coherent monitoring and assessment framework for *chlorophyll a*, an indicator relevant for eutrophication (D5), for the North Sea subregion. This includes new threshold values for chlorophyll and nutrients and cross-border assessment areas with similar ecological and physical functioning. Satellite observation is introduced as a common and reliable source of chlorophyll a data, yielding unprecedented spatial and temporal resolution. In addition, it is shown that satellite observation can be used for estimation of primary production, which is relevant for both eutrophication and foodwebs (D4).

The entire monitoring and assessment cycle is addressed to support the application of the project results by North Sea countries and in OSPAR. The JMP EUNOSAT approach has in principle been approved in OSPAR, and application will be tested for the next eutrophication assessment under the QSR 2023. Proposals for operational collaboration in North Sea monitoring and data management will contribute to improving the quality and efficiency of eutrophication monitoring. The approach can in principle be used for other sea areas.

We acknowledge that these proposals for better coherence require North Sea countries to adapt current practices, which may have consequences for national time series and may trigger organisational changes. The project identified the following drivers for change:

- *policy*: improving coherence of assessments (MSFD, OSPAR). This is an explicit requirement under the MSFD and regularly assessed by the European Commission on the basis of Art 11 reporting;
- *money*: the need for cost effective monitoring programs while more data are needed for MSFD implementation;
- *technology push*: more and/or better data through new techniques;
- *science*: improve understanding of ecosystem functioning.

Together, these drivers are expected to enhance the willingness of North Sea countries to adapt their monitoring programmes for eutrophication, in spite of national and institutional barriers. During the project the ideas and results were discussed with OSPAR working groups and also with HELCOM. This has provided a foundation to test and potentially accept the JMP EUNOSAT approach for a coherent chlorophyll assessment framework.

All reports can be found on the project website: *https://www.informatiehuismarien.nl/projecten/algaeevaluated/*

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1. Introduction

The main objective of JMP EUNOSAT is to improve quality and efficiency of eutrophication monitoring and assessment in the Greater North Sea subregion. The project Joint Monitoring Programme of the Eutrophication of the North Sea with Satellite data is organised in three Activities with the following aims:

a. Derivation of threshold values for Good Environmental Status (GES) for nutrients and algae concentrations (chlrophyll-a) with a common method for all North Sea countries (Activity 1, lead partner Deltares, the Netherlands);

b. Generation and validation of a coherent multi-algorithm satellite-based chlorophyll-a product for the North Sea and the suitability of these products for eutrophication assessments (Activity 2, lead partner RBINS, Belgium)

c. Definition of coherent assessment areas with similar ecological and physical functioning (Activities 1 and 2 together)

d. Development of a potential design of a future monitoring and assessment programme (Activity 3, lead partner Aarhus University, Denmark)

Together these Activities cover the entire information cycle (or chain) from policy needs, including assessment framework and definition of indicator, via the collection of chlorophyll data (with special focus on reliable satellite products), combining chlorophyll data from existing and new sources, and data management to coherent assessment and reporting. Thereby the project contributes to a major challenge in OSPAR, *i.e*. shifting from national eutrophication assessments that are difficult to compare across national borders to a coherent joint assessment for the Quality Status Report 2023 and the 2024 reporting under the EU Marine Strategy Framework Directive (MSFD) . Furthermore, the project develops options for operational collaboration between North Sea countries. Figure 1 depicts the elements considered and the products we deliver. This report presents an overview of these products. For further details the separate Activity reports should be consulted (Blauw et al., 2019; van der Zande et al, 2019, Markager et al., 2019).

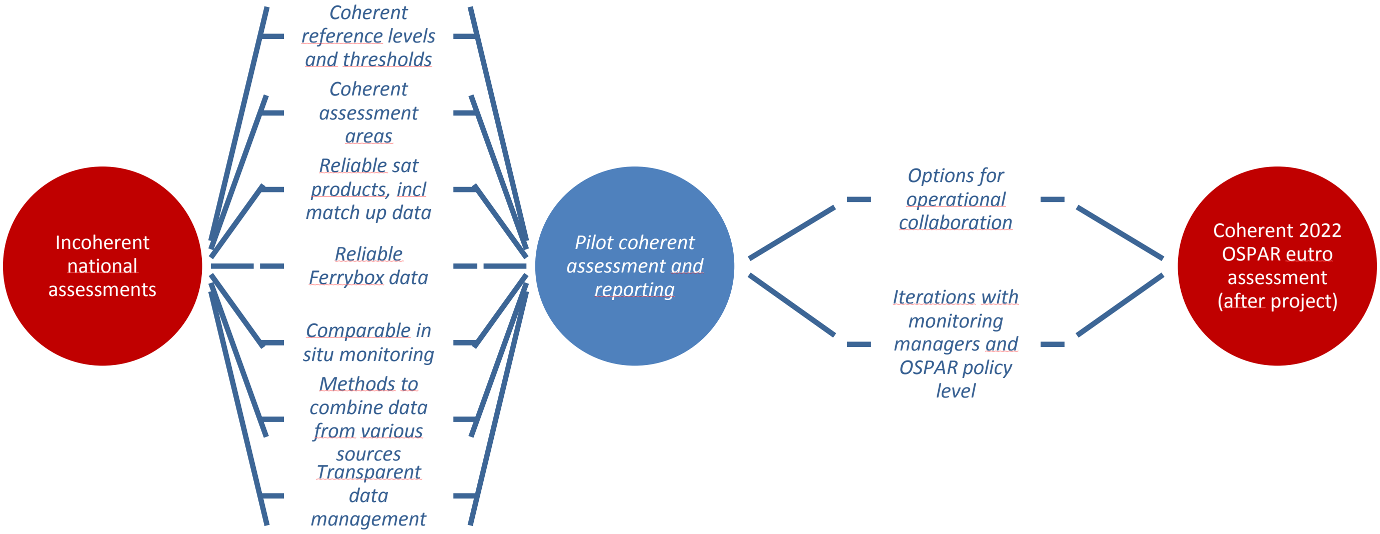

Figure 1. Elements of eutrophication monitoring and assessment considered by the JMP EUNOSAT project that contribute to future coherent assessments for the North Sea. JMP EUNOSAT products are shown in blue italics.

2. Current situation: national assessments

One of the project aims is to determine coherent threshold values (also named assessment levels in OSPAR) for the whole North Sea in a similar way as countries around the North Sea have used before. Within OSPAR, assessment levels for chlorophyll a and nutrients are commonly defined as a justified area-specific percentage deviation from background conditions not exceeding 50%, i.e. ≤50% above chlorophyll and nutrient concentrations under "natural reference conditions". The project investigated approaches used by North Sea countries to determine these natural reference conditions, since differences therein lead to incoherent assessment outcomes, see Figure 2. In most cases a historical reference year was used between 1880 and 1930's. Some countries used geographical reference sites. Furthermore, there are two types of models in use to estimate natural reference conditions: regression models and process-based models.

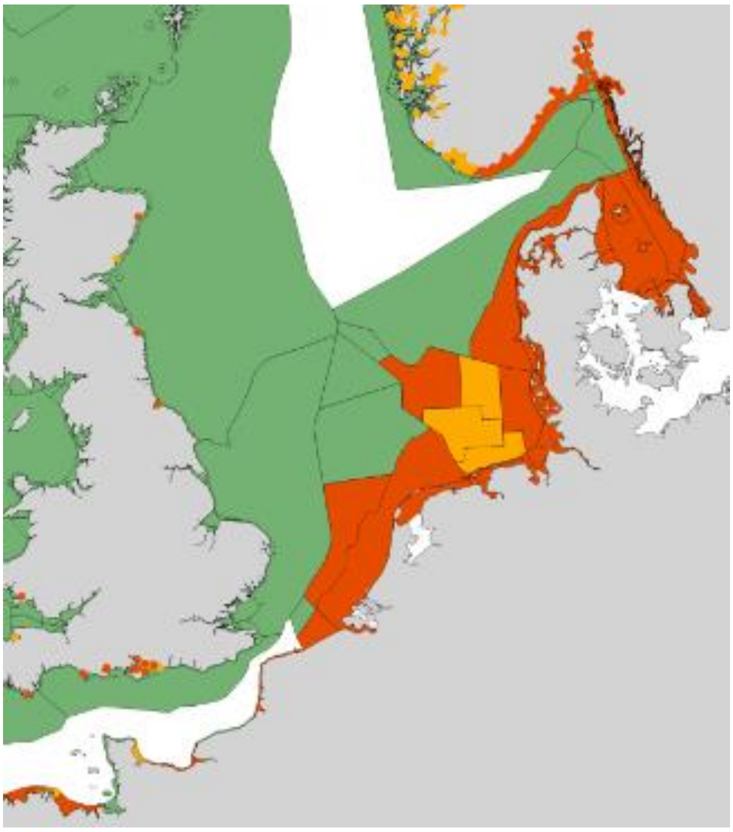

Figure 2. Challenge: incoherent OSPAR eutrophication assessment 2006-2014, based on in situ data

3. Elements of coherent eutrophication monitoring and assessment

3.1. Coherent background and threshold concentrations

3.1.1. Stepwise approach

The current approaches to define nutrient and chlorophyll a background concentrations differ between North Sea countries. For the purpose of coherence between countries, the project proposes a common 'average' approach using 1900 as reference year. Threshold concentrations of nutrients (dissolved inorganic nitrogen and phosphorus, DIN resp. DIP) and chlorophyll-a are defined for this study as 50% above concentrations in 1900 (*ie.* 150% of these concentrations). For DIN and DIP we have used winter means (December – February) and for chlorophyll-a growing season means (March – September). Figure 3 shows the workflow used to estimate nutrient and chlorophyll concentrations in 1900.

First, nutrient loads for 1900 were estimated by SMHI (SE) with the European hydrology model E-HYPE and historic information on land use, point sources and diffuse sources (agriculture), population density and waste water treatment (HYDE database). Second, the resulting total nutrient concentrations in the North Sea have been estimated by Deltares with the physical transport model: DFM (Delft Flexible Mesh). As a third step the chlorophyll-a concentrations corresponding to these total nutrient concentrations in the North Sea have been estimated with a regression model. In a fourth step we estimated coherent threshold values based on the above modelling activities.

Since there are no reliable validation data available for the year 1900, we have run the same series of models for recent years and validated them with available data. The nutrient inputs from rivers (step 1) have been validated with existing OSPAR data sets, *i.e.* the database of Riverine an Indirect discharges and data collected for eutrophication modelling. The nutrient concentrations at sea (step 2) have been validated with in situ monitoring data collected from the project partners. The chlorophyll-a concentrations at sea (step 3) have also been validated with these in situ data and additionally with the coherent satellite data, produced as part of the project.

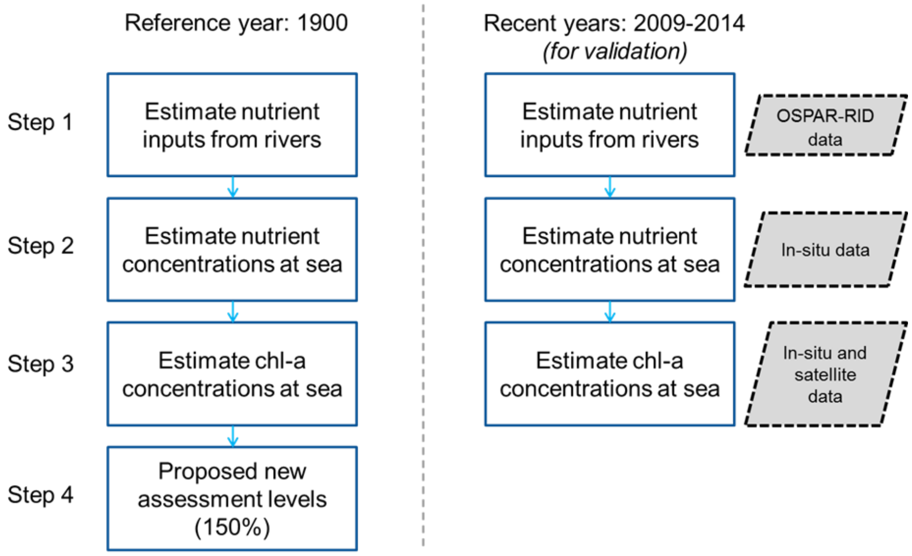

Figure 3. Stepwise estimation of nutrient background concentrations in the reference year 1900 and related threshold values (left), using recent measurements for validation of the models (right).

3.1.2. Proposed new background and assessment concentrations

The validation of the models showed a reasonably good correspondence between model results and observed data in most areas of the North Sea, although in some areas, such as the outflow of the Baltic Sea, further model improvement is needed. We proceeded to use the model, with additional information for the Baltic inflow, for estimation of nutrient and chlorophyll a background concentrations (year 1900) and assessment levels (50% above background concentrations). The JMP-EUNOSAT approach ensures coherence between nutrient (DIN) assessment levels and chlorophyll assessment levels. Figure 4 shows the newly proposed assessment levels for winter mean DIN (left) in comparison with the current OSPAR assessment levels (right). Figure 5 shows the newly proposed assessment levels for growing season mean chlorophyll-a (left) in comparison with the current OSPAR assessment levels (right). Note that the current OSPAR assessment levels are for 90-percentile values. Therefore, we multiplied the JMP-EUNOSAT assessment levels for growing season mean by 2 to approximate growing season 90-percentiles. The proposed assessment levels are coherent between countries and have a much finer resolution than the current ones.

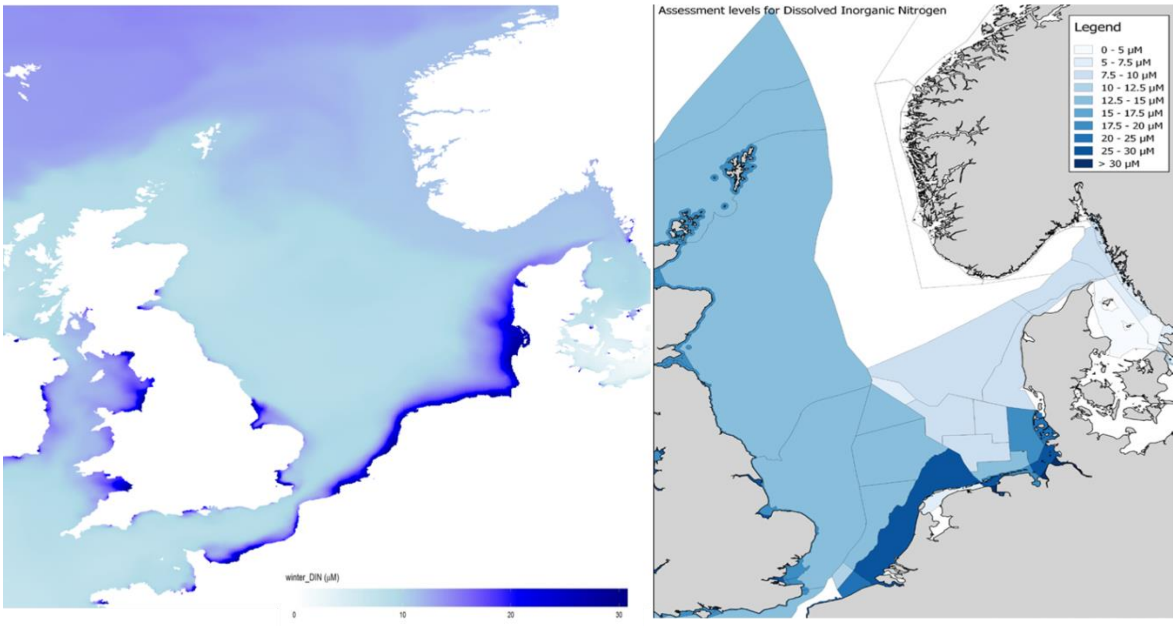

Figure 4: JMP-EUNOSAT assessment levels for winter mean DIN (left) in comparison with current OSPAR assessment levels (right)

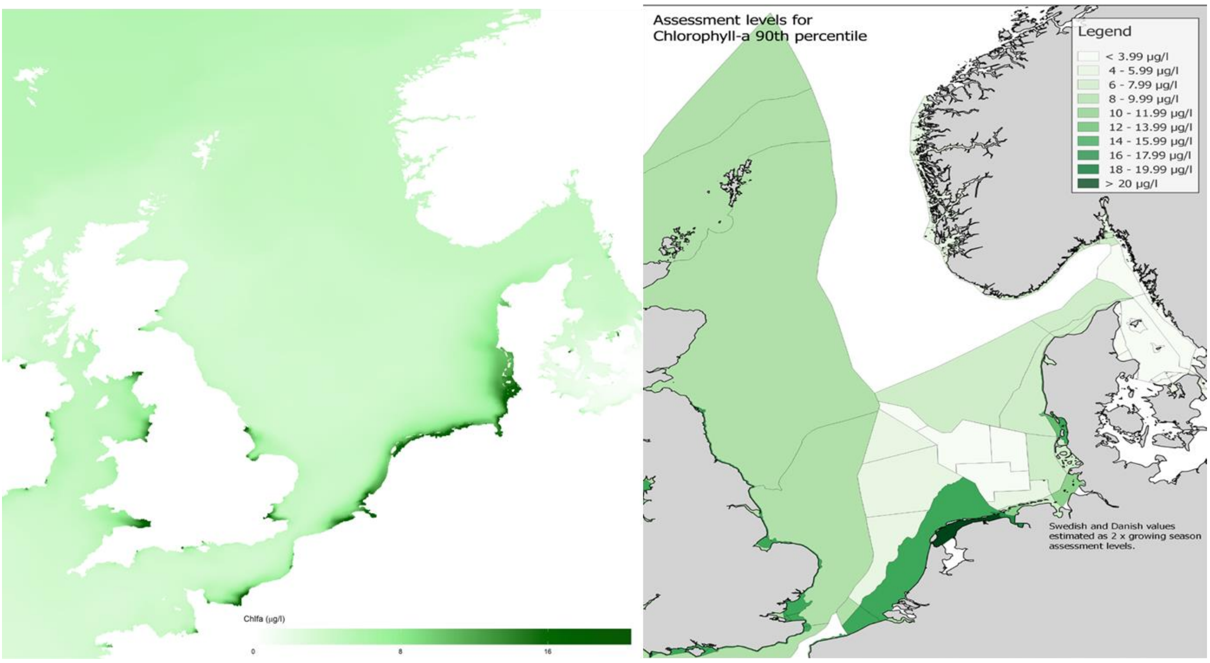

Figure 5: JMP-EUNOSAT assessment levels for growing season 90-percentile chlorophyll-a (left) in comparison with current OSPAR assessment levels (right)

3.2. Coherent assessment areas

Current assessment areas used for OSPAR assessments (for example: OSPAR 2017) are defined by first splitting up the North Sea by national boundaries and then splitting up these in smaller areas, with similar ecological and physical functioning. Since countries have used different approaches and criteria for the definition of national sub-areas the resulting definition of assessment areas throughout the North Sea does not consistently reflect the ecological functioning of the North Sea (Figures 4 and 5) and results in inconsistencies in the assessments of environmental status. In the JMP-EUNOSAT project we have used a different approach:

1. We first defined areas with similar ecological and physical functioning throughout the North Sea, based on spatial and seasonal patterns of chlorophyll and primary production in satellite data;
2. Then split up these cross-border coherent areas into national sub-areas, so countries can take responsibility for their own part of the cross-border assessment areas;
3. These national sub-areas can be further subdivided into smaller areas, depending on preferences and practical considerations of countries. This would allow for example to assess changes in areas that are affected by specific river catchments.

The new assessment areas reflect those characteristics of the North Sea ecosystem that are relevant for the assessment of eutrophication. In an assessment area shares similar environmental conditions occur, which can be distinguished from the conditions in other areas. Relevant environmental conditions include both physical, chemical and biological factors and anthropogenic pressures: depth, salinity and stratification (Figure 6). The criteria for these three factors (i.e. the values to subdivide areas) were set at specific values that ensured a good match with the areas defined by chlorophyll satellite observations. For example, areas were subdivided at salinity of 32 and at depth of 35 m. Additionally, geographical areas were distinguished, such as the Channel, Irish Sea and Kattegat.

Figure 6 shows how the cross-border newly proposed assessment areas compare with national boundaries and current assessment areas. Comparing the newly proposed assessment areas with the current assessment areas the main difference is that different water types (for example 'coastal waters' or 'Dogger Bank') are now defined on the basis of common criteria across national borders and form coherent sub-areas.

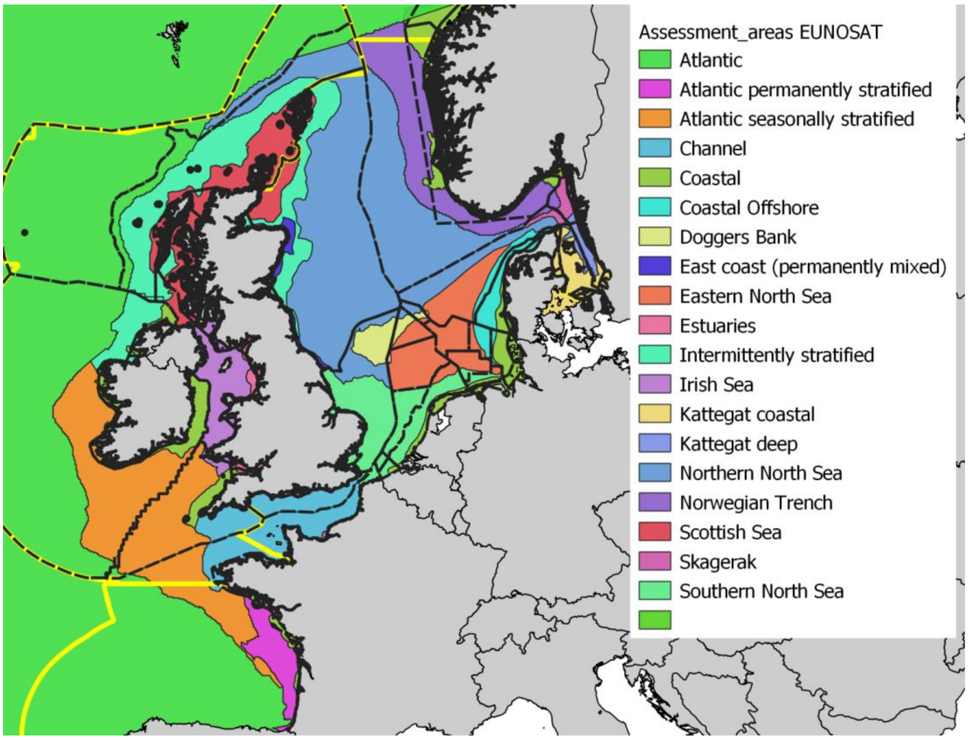

Figure 6: Comparison of 'new' assessment areas with current COMP assessment areas (indicated with black broken lines). Borders between MSFD sub-regions are shown by yellow lines.

3.3. Reliable satellite products, including match up data

The technical objective of the Activity 2 of the JMP EUNOSAT project was to generate a coherent multi-algorithm satellite-based chlorophyll product from publicly accessible satellite-based chlorophyll products available from Copernicus Marine Environment Monitoring Services (CMEMS), European Space Agency (i.e. ODESA) and other data providers (*i.e.* IFREMER). To achieve this, we determined the validity of these core ocean colour products for different water types (*e.g.* clear, turbid or coloured dissolved organic matter (CDOM) rich waters) and upgraded these satellite products to operational and coherent monitoring products usable for eutrophication assessment in the Greater North Sea through a quality control and merging process. This step enabled the progression from point-by-point and country-by-country analyses, to basin-wide analysis with data that cover gradients in the ecosystem system. The choice of satellite product is thereby determined by environmental conditions, rather than national boundaries of the Contracting Parties, resulting in one coherent chlorophyll product for the North Sea (Figure 7).

Satellite data are available from 1998 to date, produced by multiple satellites of US and EU origin. The new EU Sentinel 3 satellites (twins, to account for failures) will deliver data from 2016 to 2036. They have a 300m spatial resolution and pass over the North Sea every day. This results in approximately two useful observations per location per week during the growing season, depending on cloud cover.

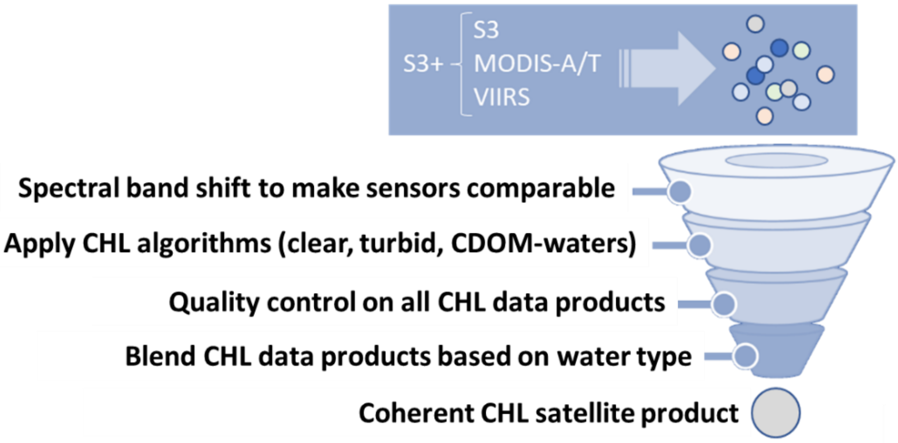

Figure 7: Generation of quality controlled coherent chlorophyll products, based on observations from different historic and currently operational satellites, including the new Sentinel 3.

We started from a collection of well-validated operational satellite-based chlorophyll products (or algorithms) for the Greater North Sea[1]. For each of these products it was determined for which water types, described in terms of remote sensing reflectance (Rrs) spectra, they provided the most accurate chlorophyll estimations (i.e. relative error < 50%), based on a variety of reference datasets from the CCRR project[2] and MERMAID database. Results show that

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[1] 1) CMEMS OC-CCI (CMEMS no. 67),
2) CMEMS OC4 adapted to Baltic waters (CMEMS no. 80),
3) Red/NIR algorithm (Gons) applied to OC-CCI remote sensing reflectance product (CMEMS no. 66) and
4) FUB-WEW v4.0.1 applied to the MERIS archive.

[2] Coast Colour Round Robin (CCRR) data set published by Nechad et al. (2015). The CCRR project (http://www.coastcolour.org) funded by the European Space Agency (ESA) was designed to bring together a variety of reference datasets and to use these to test algorithms and assess their accuracy for retrieving water quality parameters. This information was developed to help end-users of remote sensing products to select the most accurate algorithms for their coastal region

by applying this quality control per algorithm, performances of the selected algorithms in optically complex coastal waters are improved and almost reach the standards expected in the open ocean (*i.e*. 30% error). In the next phase, the best combination of quality controlled chlorophyll algorithms is determined to produce a quality controlled multi-algorithm satellite chlorophyll product based on the best suited algorithm/water type combination.

The suitability of the blended chlorophyll product for eutrophication assessment was evaluated by a comparison analysis with *in situ* datasets for all assessment areas in the North Sea. Time series were extracted from the satellite database for all in situ stations and for each time series the monthly means were calculated, from which yearly means where obtained for the growing season March-October incl.. This was done to avoid impact from irregular sampling. Time series with *in situ* and satellite data for at least 8 months were accepted in the validation study. Figure 8 shows the results from a regression analysis comparing yearly chlorophyll mean values for both *in situ* and satellite data sources for the different JMP-EUNOSAT partners.

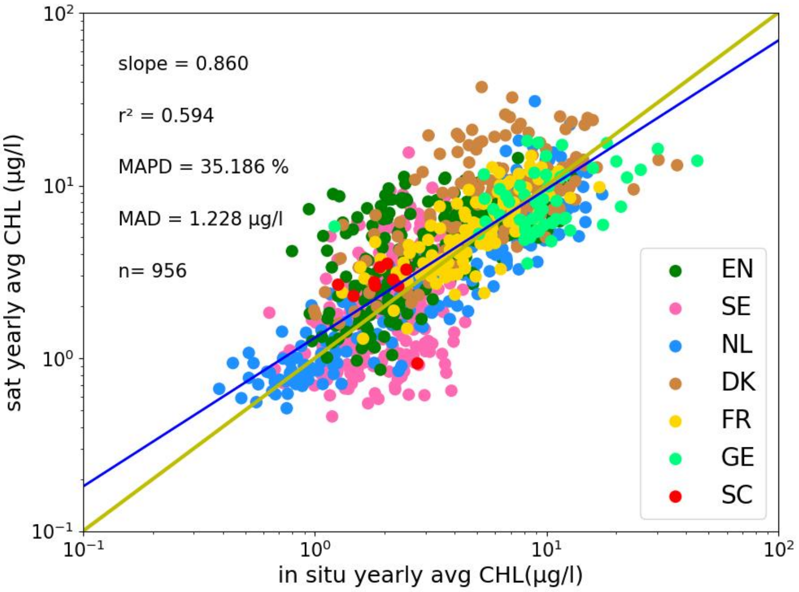

Figure 8. Scatterplots of yearly mean (average) chlorophyll concentrations based on in situ *and satellite chlorophyll observations for the North Sea countries. The relationship between both data sets are described by the Median Absolute Difference (MAD) and the Median Absolute Percentage Error (MAPD). The determination coefficient (r²) and the slope characterizes the regression. Axes are log-transformed.*

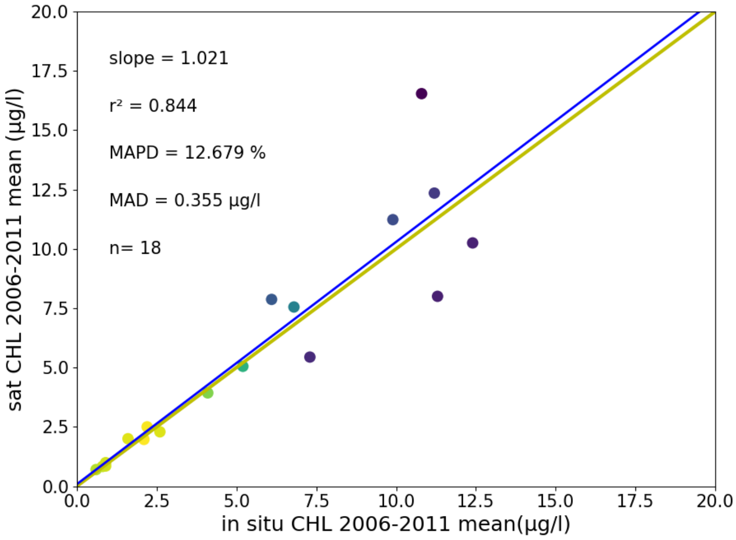

Figure 9. Scatterplot of mean chlorophyll concentrations for the period 2006-2011 based on in situ and satellite chlorophyll observations for Dutch waters. The relationship between both data sets are described by the Mean Absolute Difference (MAD), Mean Absolute Percentage Error (MAPD). The determination coefficient (r^2) and the slope characterizes the regression.

Figure 9 depicts regression between mean growing season chlorophyll a concentrations of in situ versus satellite observations at all Dutch monitoring stations. These represent coastal and offshore waters. In situ samples were analysed using HPLC, which is the preferred analytical method for satellite validation. There is a good fit in a wide range of chlorophyll-a concentrations.

As seen in Figures 8 and 9 the fit between in situ and satellite observations differs between countries, which is due to a combination of factors, including differences in water types at the monitoring stations, *in situ* analytical method and proximity to the coast. Note that these *in situ* data have not been collected for the purpose of satellite validation. JMP EUNOSAT proposes collaboration between North Sea countries to populate a database of 'match ups', *ie.* in situ samples taken in a window of two hours of satellite overpass under clear sky conditions.

The quality control and merging procedure was tested on Sentinel-3 OLCI images. Although more validation results are still needed for the OLCI sensors, results show good agreements with the applications on MERIS images, which suggest that applied the presented methodology will help to accurately estimate chlorophyll in the North Sea for the Sentinel-3 era which will continue up to 2036.

Satellite observation of the eastern part of the North Sea, ie North and East of Jutland, appeared difficult. The JMP-EUNOSAT coherent satellite product includes an algorithm specifically developed for Baltic conditions (OC4_BAL). However, the validation procedure could not satisfactory be applied in this area, due to high CDOM concentrations that increased the noise in the satellite signal (*cf*. Activity 2 report, section 2.3.11). We considered the results of the OC4_BAL algorithm acceptable only between 1 and 10 µg chlorophyll/l and when CDOM concentrations were not too high. As a case study for complex waters due to high CDOM concentrations the project compared the OC4_BAL chlorophyll product with an extensive *in situ* dataset of the Kattegat-Belt area in the period 1998-2016. This showed that satellite observations work quite well for open water conditions in this area, particularly in years when the MERIS satellite was available (Figure 10, period from 2003 to 2011). Outside of these period data from other satellites have been used, yielding underestimates and overestimates of chlorophyll concentrations respectively, *i.e.*

an upward time trend, while the trend observed with *in situ* data was actually downward. Therefore, scaling factors were applied in this case study, assuming that the *in situ* data are more accurate.

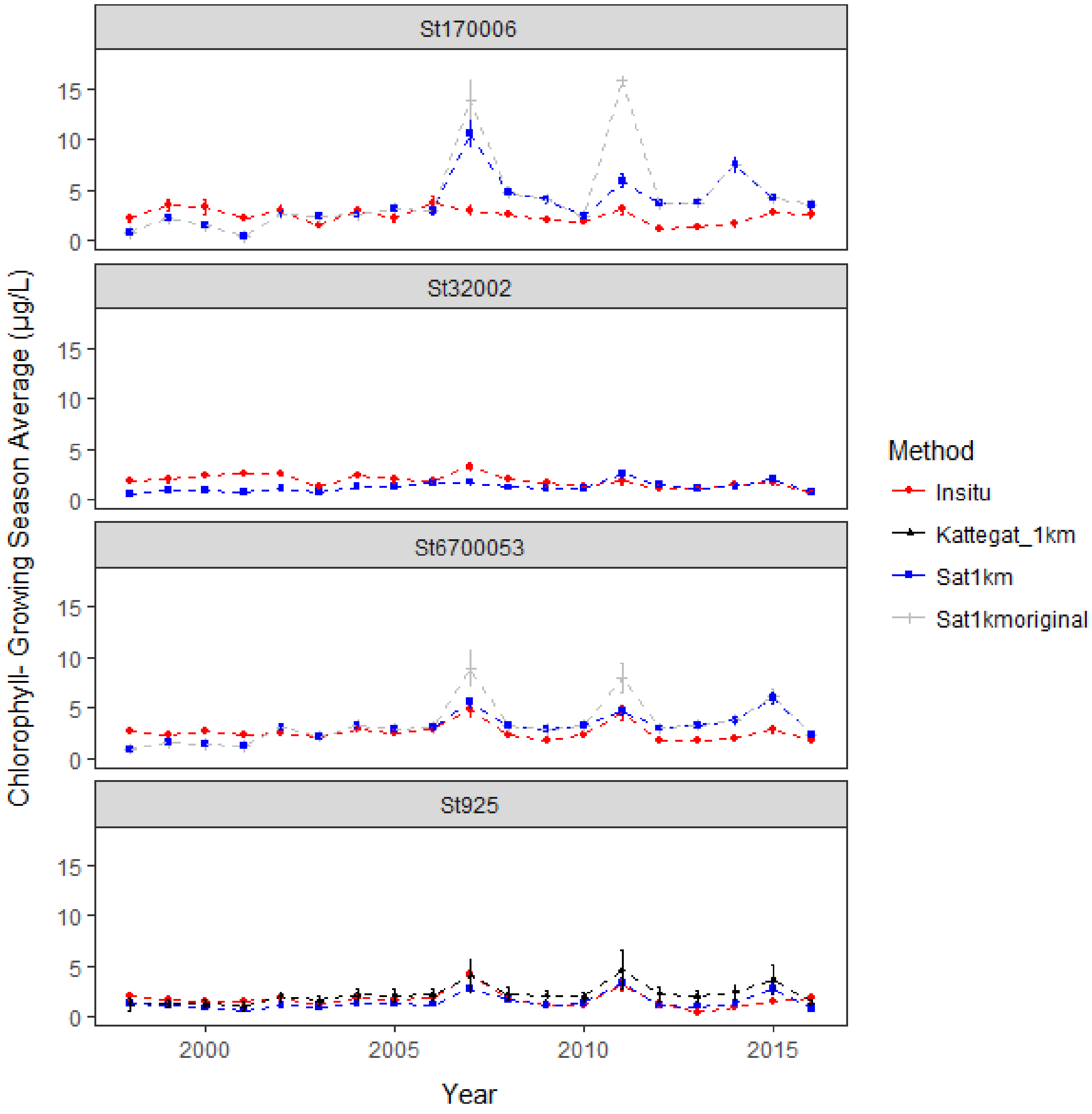

Figure 10: Growing season mean values for four stations in the Kattegat–Belt Sea area. Red lines are estimates based on in situ values. Grey lines are satellite estimates (Van der Zande et al. 2019) for 1x1 km grid cells. In coastal areas, within ca. 5 km from the coast (1st and 3rd panel), a number of erroneously high values occur (up to 6 standard deviations above the highest recorded in situ value over 19 years with about 600 observations in total). Open water stations (2nd and 4th panel) perform better than coastal stations. The blue line is corrected satellite-estimated values where values above one standard deviation for the month are removed. The black line in the lower panel is a time series based on 1x1 km grid cells covering the entire Kattegat outside 5 km from the coast. The EU MERIS satellite, which had sensors comparable to the new EU Sentinel satellites, was operational from 2003 to 2011.

PML (UK) processed and analysed a dataset of 20 years of primary production estimates from satellite data for the Greater North Sea. These data corresponded well to observations in Atlantic waters. Unfortunately, observed data on primary production data in the North Sea were lacking, hampering validation in those waters. Seasonal patterns in primary contribution informed the development of ecologically coherent assessment areas. Furthermore, baseline values in primary production over the OSPAR region using satellites were developed. These are however, not necessarily coherent with the background concentrations established for chlorophyll a.

A satellite product for primary production can significantly support the development of an indicator for food webs: MSFD descriptor D4C4 – Productivity of the trophic guild is not adversely affected due to anthropogenic pressures. So far this indicator could not be used because there are hardly any monitoring data available for primary production. In the field this is a time consuming and expensive observation to make.

3.4. Reliable Ferrybox data

The project embraced the added value of Ferrybox observations, that offer high frequency data at relatively low costs, next to satellite and national in situ monitoring programmes. Ferrybox data proved very helpful for the validation of our models.

This user perspective inspired the establishment of a new Ferrybox on a cargo line between Tanager (NO), Rotterdam (NL) and Immingham (UK) through a Memorandum of Understanding between project partners NIVA (NO) and RWS (NL). Unfortunately, progress in the installation of this line was such that no new data could be provided during the course of the JMP project. The Ferrybox-line is expected to be operational mid-2019. Collaboration with the European Ferrybox network (www.ferrybox.com) and NorSOOP (Norwegian Ships Of Opportunity Program for marine and atmospheric research (www.niva.no/norsoop) ensures the use of state of the art techniques and scientific knowledge in this area.

This ship has relatively good space for an installation and for future expansions. The operation will start with Chlorophyll-a fluorescence, CDOM fluorescence and other standard sensors , *ie*. temperature, salinity, oxygen, turbidity. It will also operate an automatic water sampler that could take samples during a satellite overpass. For the second phase we foresee to also bring on board more advanced sensors and analysers such as a flowcytometer and Fast Repetition Rate Fluorometry (estimation of primary production). The high frequency of the data collected provide insight in the ratio between the fluorescence signal and the concentration of chlorophyll a (from auto sampler data), and spatial variability. With Ferrybox systems collecting water from a depth of 5m it is important to determine possible differences with the same parameters measured at the surface (measured by satellites). These relationships are region specific. Sufficient attention to maintenance and QC is essential. For satellite product validation above water a radiance sensor can be used to compare and control the water leaving reflectance and this ship has a good design to try such an installation.

3.5. Comparable *in situ* monitoring

Various techniques for analysis and detection of chlorophyll a in water samples are in use in North Sea countries. The options are spectrophotometric detection after extraction in ethanol or acetone, fluorometric detection after extraction in ethanol or acetone or HPLC after extraction in acetone. The latter method is the most specific as it can separate the different pigments and types of chlorophyll, but its costs are significantly higher than for other techniques. All other methods will, to a varying degree, co-measure other forms of chlorophyll than chlorophyll a. The conversion from one method to another depends on the composition of the phytoplankton community. However, there is reasonable agreement between the methods, except that HPLC-values for chlorophyll a are lower than chlorophyll values obtained using the other methods. A comparison in Scottish waters suggest a factor of approximately 0.8. However, this factor needs further validation.

Other aspects of comparable in situ observations are vertical distribution of algae and diurnal and seasonal patterns in the ratio between fluorescence (fluorometry) and chlorophyll concentration. The latter is important in the context of automated sampling techniques, *eg*. Ferryboxes. We suggest that calibration techniques should be developed and applied. Vertical distribution and other issues can be accounted for in a common protocol for sampling and analytical procedures. The project provides recommendations for such a protocol (Activity 3 report).

However, it is for the North Sea countries to decide whether to aim for harmonisation of methods (*eg*. all countries using HPLC or a cheaper alternative such as fluorescence on extracts) or to allow for the use of different methods for measuring chlorophyll. The latter will require more effort on inter-comparisons and submission of metadata on methods and calibration along with values to a common database.

It should be noted that chlorophyll concentration is a proxy for phytoplankton biomass. The ratio carbon to chlorophyll content of algal cells varies. It is affected by nutrient status of the cells, where the ratio is higher under nutrient depletion.

3.6. Methods to combine data from various sources

The vision of this project is that chlorophyll a data from various sources (ship base *in situ* sampling, satellite observation, automated sampling by Ferryboxes and fixed stations or smart buoys) should be used in eutrophication assessments, since each method has advantages and disadvantages in terms of spatial and temporal resolution, precision, accuracy and costs. Determinations of chlorophyll a in water samples using HPLC is considered a reliable standard among both satellite and in situ monitoring experts. Important aspects to consider in combining data are relationships or conversion factors between detection methods, spatial and temporal integration and calculation of a combined annual mean or 90-percentiles. In the project these issues were discussed, but no final conclusions have been drawn.

Conversion factors between automated fluorometric detection (as in Ferryboxes or smart buoys) and in situ water sampling for chlorophyll can repeatedly be established during the growing season and are area specific. This is current practice in sampling programmes of Norwegian waters using Ferryboxes equipped with water sampling devices. This enables full exploitation of cheap automated techniques with high spatial and temporal resolution at long transects and throughout the year.

Comparison between satellite observation and in situ sampling is described in section 3.3. However, in optically complex waters, where the relationship may not be sufficiently reliable, a correction factor can be applied, assuming that the in situ values represent the best estimate of chlorophyll. This is further explained in the Kattegat case study (section 3.3 and Activity 3 report). The method used by HELCOM applies weighting factors based on expert judgement (for example: factor 0.45 for satellite and 0.55 for *in situ* seasonal means) before calculating the combined chlorophyll seasonal mean, is a simple, although arbitrary solution. This may be improved using the accuracy of each of the chlorophyll time series, *i.e*. more weight given to *in situ* observations when accuracy of in situ chlorophyll time series is higher than satellite chlorophyll time series and *vice versa*. A method based on comparison of actual *in situ* and satellite sampling frequencies with long-term reference time series (satellite climatology) provides an evaluation of the quality of the data sets (*cf.* Activity 2 report section 4.1).

For spatial integration the simplest solution is to use grid cells, for instance the 1x1 km satellite grid cells or larger grid sizes, *eg.* HELCOM’s 20x20km, depending on the variability of the area and the spatial resolution of *in situ* monitoring stations. If an in situ monitoring station is located in a grid cell, we can calculate the seasonal means for both in situ data and satellite data. These can be averaged, with or without weighting factor. Direct calculation of a seasonal mean on all chlorophyll data in the grid cell is generally not considered acceptable, since the few in situ data (if at all available) will be drowned in a much larger number of satellite data. The underlying question is: on what basis are data being trusted? It will take some time for *in situ* monitoring experts, but also policy makers used to *in situ* time series, to accept the 'innovative' data from satellite observation. This project has contributed to that discussion, but more interaction with the earth observation community is needed.

3.7. Transparent data management

In general, the project stresses the importance of storing metadata together with chlorophyll concentrations and transparency of the database to enable comparisons between countries using different analytical methods and sampling procedures, and with historic data. This is especially important when new methods are implemented (comparability of time series).

Metadata are all other data than the value of the variable – here chlorophyll concentration (µg/l), time, position and depth of sampling. Metadata may describe the analytical method, calibration data, gear for collection of samples, algorithms used for satellite observations, instrumentation on ferrybox systems etc.. The OSPAR JAMP Eutrophication Monitoring Guidelines: Chlorophyll a in Water (OSPAR, 2012) describe sampling and analytical procedures and allow for the use of different methods. Sometimes metadata about the actual methods are reported to ICES.

OSPAR developed a joint plan of work for closer harmonisation between the common indicators, the Common procedure for the identification of eutrophication and the MSFD Commission Decision criteria on good environmental status, in preparation for the QSR 2023. In a pilot study the HELCOM Eutrophication Assessment Tool (HEAT) was applied to a set of North Sea countries (Sweden, Germany and The Netherlands). The satellite data layer, that is also available in HEAT, but not yet for OSPAR assessments, was provided by the JMP EUNOSAT project. The ICES website shows how satellite data can support the assessment: https://ocean.ices.dk/core/oeat. Moreover, through this tool transparency in the origin of the data and in the methods used is greatly enhanced. This in turn is a prerequisite for improving coherence between countries.

4. Pilot coherent assessment and reporting

4.1. Assessment approach

The JMP-EUNOSAT project aimed at an assessment approach that would give coherent, reliable and robust assessment results that reflect relevant information on ecosystem health with minimal noise. Noise may result from natural variability. Or it could result from an inadequate number of observations that are not representative for the season mean or area mean. By using satellite data and spatially variable assessment levels within assessment areas the effect of spatial under-sampling is reduced. The satellite data also provide a higher temporal resolution of chlorophyll observations, which reduces the effect of temporal under-sampling where spring blooms may be randomly included or excluded from the observations.

We also propose to pre-process the data in a way that reduces random effects on the assessment by using 1) 6-year means for the assessment and 2) means instead of 90-percentiles and 3) yearly means instead of growing season means. The use of 6-year means reduces the effect of inter-annual natural variability in chlorophyll concentrations. Estimates of means are much more robust than estimates of 90-percentiles, especially when bloom events are short-lived and data are not normally distributed over the season (typical for phytoplankton) and have a limited temporal resolution. The growing season has been defined differently between different countries so far, which is a source of incoherence between countries. Moreover, in some countries, such as Denmark, blooms regularly occur outside the growing season defined for that country.

In the JMP-EUNOSAT project three changes to current assessments are proposed that may possibly affect the outcome of the assessments: 1) the use of coherent satellite data additionally to *in situ* data, 2) the use of coherent assessment levels and 3) the use of coherent assessment areas.

4.2. Effect of using satellite data

The effect of using satellite data in comparison to *in situ* data is illustrated by a pilot eutrophication assessment of Dutch waters using the quality-controlled multi-algorithm chlorophyll products and in situ data (Activity 2 report).

Assessments using satellite data gave similar results as *in situ* data in Dutch waters at the station locations. This was to be expected from the strong correlation between *in situ* and satellite 6-year mean chlorophyll concentrations per station. Still, this approach would completely negate the advantage provide by satellite sensors in terms of spatial resolution. When considering all satellite chlorophyll observations at full resolution, the estimated area chlorophyll mean is for most areas reasonably close to the mean based on station locations only when the areas are relatively homogeneous with respect to water quality indicators. In areas with strong spatial gradients, the assessment results are very sensitive to the area boundaries and the choice of *in situ* monitoring locations.

4.3. Effect of new assessment levels

A solution for this problem is the use of spatially variable chlorophyll assessment levels with a spatial resolution of 1x1km corresponding to the grid used for the satellite data. This enables a pixel by pixel eutrophication assessment by directly comparing the satellite data with the assessment levels. Spatially variable assessment levels instead of fixed levels result in a more consistent relative exceedance of the assessment levels throughout the assessment area. Consequently, the result is less dependent on the definition of assessment areas and choice of monitoring locations. Such spatially varying assessment levels allows for making better use of the full spatial resolution that satellite data can provide and improve understanding of the effectiveness of management measures. Figure 11 shows the assessment result at high spatial resolution for chlorophyll-a using satellite data for 2005 – 2010 and novel proposed assessment levels. Circles represent the assessment results at monitoring locations, using local *in situ* data. Lines indicate present OSPAR assessment areas for eutrophication.

This assessment result is still affected by limitations of our relatively simple model, without atmospheric deposition of nitrogen or sinking of organic matter during stratified conditions. Including these processes in the model is likely to considerably reduce the extent of the red area (eutrophication problem area) in the southern North Sea, for example.

In most areas the use of satellite data for the assessment (background colour) gives similar results to the use of *in situ* data (coloured circles). In case of different results further study is needed to find out which of the two data sources is most reliable. In some cases the number of *in situ* data may be very limited and do not cover the entire growing season. Hence, the season mean estimate based on satellite data may be more reliable. In other cases (particularly in turbid and/or CDOM rich waters close to the coast) the satellite data may be less reliable than the estimate based on *in situ* data. A similar approach can be taken for the use of Ferrybox data. Ideally the three data sources would be integrated in one optimally reliable information product. This requires more research.

The effect of the use of modelled chlorophyll-a estimations, which does not perfectly correspond to chlorophyll estimations based on satellite data, is illustrated by Figure 12. This Figure shows the assessment result if modelled chlorophyll concentrations for recent years are used for the assessment instead of the satellite data. In this case the estimate for the recent years is completely coherent with the estimate for the reference situation and the extent of areas that are labelled as problem areas is much reduced.

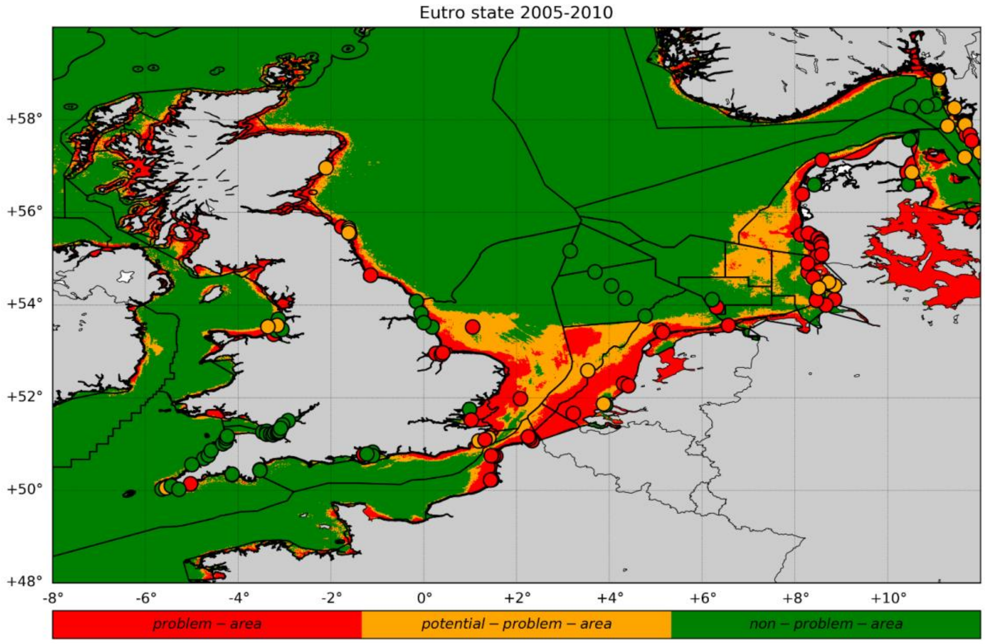

Figure 11: Assessment result (expressed as ratio of observed chlorophyll-a concentrations divided by assessment level) at high spatial resolution for satellite data (2005 – 2010 growing season mean) and novel proposed assessment levels. An uncertainty of 10% is assumed above and below ratio=1 (amber). Circles represent the assessment results at monitoring locations, using local in situ *data. Lines indicate present OSPAR COMP assessment areas for eutrophication.*

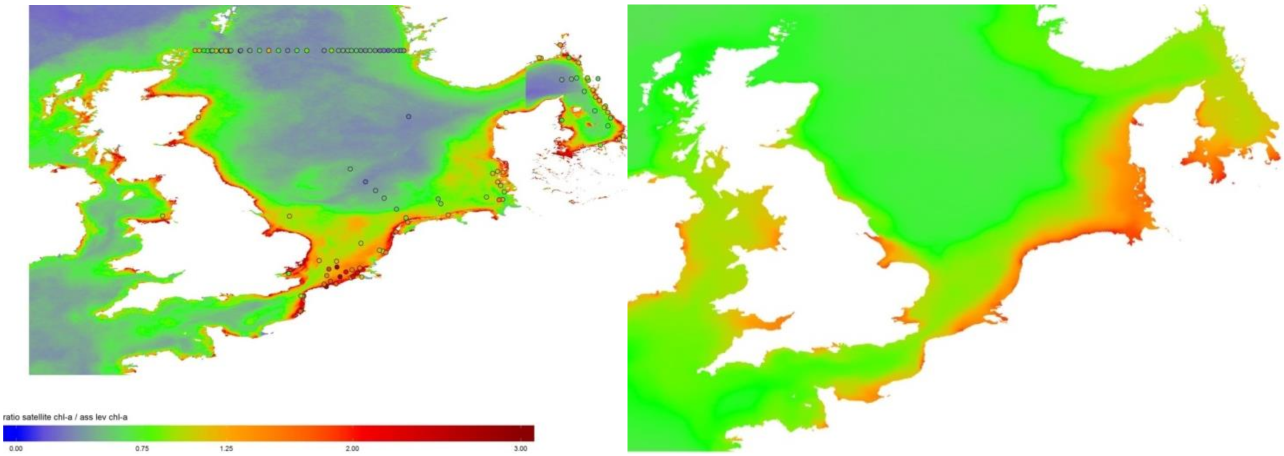

Figure 12: Comparison of assessment results using satellite data as assessment data (left) and using model data for recent years as assessment data (right). The colours reflect the ratio between observed or modelled chlorophyll concentration and the assessment level. Values above the assessment level (ratio=1) are shades of orange or red. Circles represent the assessment result using local in situ *data.*

In conclusion, the assessment result is strongly affected by the estimation of background concentrations. Therefore, we recommend to estimate the background and assessment levels again, but with a more advanced model. The JMP EUNOSAT approach achieves coherence in assessment levels between countries and between eutrophication indicators. The high spatial resolution of the satellite data and the assessment levels furthermore allows for a more detailed analysis of possible causes and solutions of eutrophication phenomena.

4.4. Effect of new assessment areas

For a tabular representation of the assessment result and for the analysis of time series per area it is practical to summarize assessment results per assessment area. Figure 13 shows the assessment result, summarized as uniform colours per assessment area, following the procedure described below. Comparing figure 13 right panel to figure 11 shows that for example in the UK southern North Sea assessment area in the old OSPAR assessment area the southern part is red/orange and the northern part is green. The new assessment areas, discriminating between the seasonally stratified and the mixed part, do not mix up the assessment results of these very different areas. The newly proposed assessment areas do not yet separate near-shore WFD waters from the coastal waters further from the coast. This results in large orange areas along the UK north-west coast for example, that are actually a mixture of near-shore red areas and coastal green areas (see Figure 11). Therefore, in a next step we recommend to subdivide the near-shore areas using WFD assessment areas.

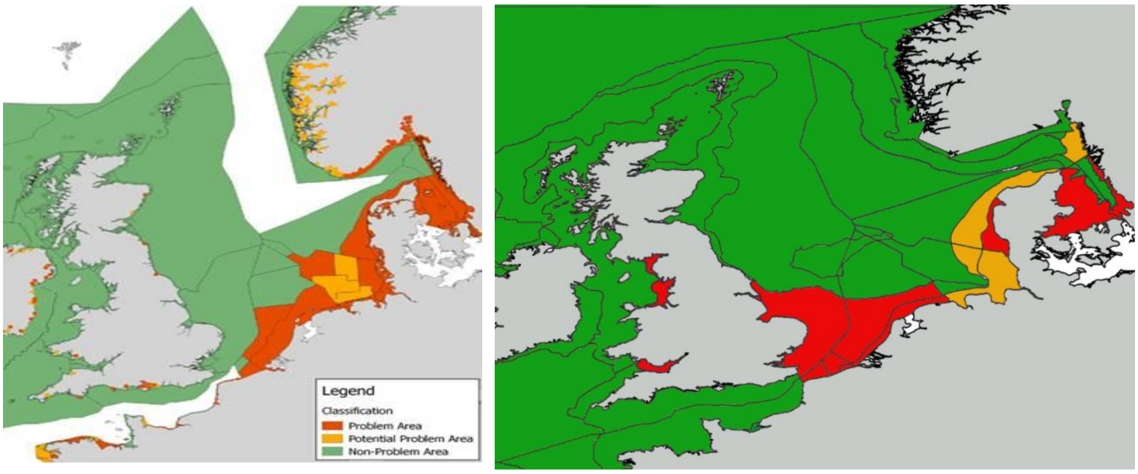

Figure 13: New assessment result using JMP-EUNOSAT satellite data (2006-2011), JMP-EUNOSAT assessment levels and JMP-EUNOSAT assessment areas (right) and overall OSPAR assessment results from the most recent comprehensive procedure report (2006-2014)(left). In the right panel the ratio of observed chlorophyll-a concentration and assessment level is colour coded (explained in the text below). An uncertainty of 10% is assumed above and below ratio=1 (amber). Lines represent the original COMP assessment areas (left) and the newly proposed assessment areas (right). Country borders are indicated in both panels.

The high spatial resolution data can be summarized per assessment area in several ways. In the map example above (figure 13, right panel) we have divided the chlorophyll-a concentration from satellite data (6-year seasonal mean) by the local chlorophyll-a concentration of the assessment level. This resulted in values for each 1x1km grid cell: values lower than 0.9 are classified as non-problem area (green), values above 1.1. are classified as problem area (red) and values between 0.9 and 1.1 are classified as potential problem areas (orange), to take into account some uncertainty margin in both the satellite data and the assessment level. To determine the uniform colour per assessment area we took the mean of these ratios and colour-coded them in the same way as described above. However, the traffic light colour system, using two (in the MSFD: below or above GES) or three (in OSPAR's COMP, the third indicates potential problem areas), is quite limiting in terms of assessing gradual improvement of the GES of an assessment area. With a satellite-based eutrophication product it is possible to accurately determine the extent of the area that is not subject to eutrophication and determine its evolution in time as an objective indicator of changes in eutrophication pressures through time. Apart from plotting uniform colours per assessment area on maps these summary statistics (both mean distance to GES and % area not subject to eutrophication) can be used in tables or for plotting time series.

5. Translation to operational monitoring and assessment

5.1. Options for operational collaboration

Regarding the organisation of ship-based sampling the project identified opportunities and challenges in operational collaboration. This includes integration of in situ chlorophyll sampling, including for satellite match-ups (see section 3.3), with sampling for other purposes (*e.g.* fishing surveys), use of ships of opportunity and cross-country collaboration. The latter would be supported by an analysis of the state of the current fleet of monitoring/research vessels operating in the North Sea. The overarching goal is that once a vessel is at sea, it should solve as many tasks as possible in order to minimise operational costs and CO_2 emission related to burning of fuel.

Cross-country collaboration may involve joint programming of monitoring. Agreement on a common protocol for sampling and sample analysis would facilitate such collaboration and improve the comparability of the data and quality of the end result. Elements of such a protocol are described in the Activity 3 report. A common protocol will inevitably require that some countries change their protocol, which will have consequences for national time series. Regarding joint protocols and survey planning a previous EU project (JMP NS/CS) concluded that agreements are needed on a top level (*e.g.* Memorandum of Understanding) and subsequent levels (*e.g*. monitoring expert to monitoring practitioner), to ensure that the process is cascaded further and is effectively done. Furthermore, joint planning will be supported by sharing actual resources (*e.g*. staff, vessels, equipment) and subsequently sharing the final outcomes (*e.g*. data and knowledge) with all parties involved (Birchenough et al. 2015).

Retrieval of satellite data is rapidly becoming easier and cheaper and is now done by many institutions. Activity 2 has developed a formal procedure for quality assurance and selection of the optimal algorithms for different marine areas in the North Sea (Van der Zande at al. 2019). In this project one institute (RBINS) delivered quality controlled satellite products for the entire North Sea, as is currently practiced in the HELCOM area by the Finnish institute SYKE. The ICES data centre performs the assessment for all Baltic Sea countries and would also be able to do this for OSPAR. Such a joint approach has clear advantages in terms of coherence. However, North Sea countries may use their own national capacity to retrieve satellite products and develop algorithms suited for local conditions in the future. This may lead to diverging methods and less coherence. It is therefore essential to document algorithms and procedures used for estimating chlorophyll in public libraries. Information about the methods should be supplied as metadata along with the results when reported to international databases. A coordinating body, maybe through CMEMS, should monitor coherence between algorithms and methods related to satellite observation.

5.2. Collaboration with OSPAR policy level – contribution to next eutrophication assessment

Since 2012 EU member states need to report every 6 years on the water quality of their seas for the Marine Strategy Framework Directive (MSFD) in a consistent manner. OSPAR countries traditionally assessed the eutrophication status of their national waters using the Common Procedure. As described above this yielded incomparable results, which was most prominent in the North Sea. A joint assessment of the eutrophication status of the North Sea partially failed because of these inconsistencies (OSPAR, 2017a). The issue of coherence is therefore high on the OSPAR agenda.

Intensive collaboration between the OSPAR groups responsible for eutrophication (Hazardous Substances Committee and the Intersessional Correspondence Group on Eutrophication) and the JMP EUNOSAT project ensured mutual understanding and delivery of products answering OSPAR's needs. Some participants in the consortium are also a regular member of these groups and the coordinator and Activity leads presented intermediate and final outcomes of the project in these OSPAR meetings. The development of ecological coherent areas and related coherent thresholds for chlorophyll a and nutrients, as well as the quality controlled satellite product, have been welcomed as a major step forward.

The JMP EUNOSAT approach has in principle been approved in OSPAR, and application will be trialled for the next 2022 eutrophication assessment by a dedicated group (OSPAR, 2019). This will include testing of the modelled outcomes (in particular the background and threshold concentrations for nutrients and chlorophyll a and the assessment areas), comparison with current OSPAR and WFD assessments and improvement of the approach where needed. We foresee that this will be an iterative process where (North Sea) countries gradually approach each other and agree about GES-values for areas that are shared among several countries and where all contracting parties gradually agree on the optimal procedure.

For OSPAR the role of ICES so far has been the collection of in situ eutrophication data from OSPAR countries. However, unlike HELCOM, the assessments were performed by the OSPAR countries themselves. OSPAR recently has tasked the ICES data centre to apply the HELCOM tool to OSPAR data, also adding chlorophyll products from satellite observation. In general, further alignment with HELCOM on eutrophication monitoring and assessment is expected.

To support the development of an indicator for food webs the project will share the satellite product for primary production and the results on seasonal and spatial patterns in both chlorophyll and primary production and related ecologically coherent areas with the OSPAR Intersessional Correspondence Group on Coordination of Biodiversity Assessment and Monitoring.

6. Conclusions and recommendations

The main conclusion of this project is that satellite observation significantly enhances our understanding of eutrophication patterns in space and time, at the scale of the North Sea and beyond. This will generate more detailed understanding of the effectiveness of measures, especially when combined with modelling. Furthermore, satellite chlorophyll a products enabled the development of coherent assessment levels at the same spatial resolution as satellite data and coherent assessment areas.

The project addressed the entire chain of eutrophication monitoring and assessment, accepting that inevitably not all steps could be carried out at a high level of detail due to the limitations in time and budget. Recommendations and proposals for next steps aim at further coordination between North Sea countries to further improve coherence (Figure 14). Recommendations are summarized below (see Activity reports for more detail).

The JMP EUNOSAT approach has in principle been approved in OSPAR, and application will be trialled for the next 2022 eutrophication assessment. For this purpose the following remaining issues will be addressed by OSPAR as a first priority:

a. definition of nutrient inputs to the sea: validation of the E-HYPE model outcomes and further consideration of factors affecting the modelled 1900 riverine loads;
b. for a more accurate description of nutrient and chlorophyll concentrations at sea, the use of a 3D coupled physical-biochemical model and the addition of atmospheric inputs and the addition of exchange processes with the sediment, are recommended;
c. use of WFD threshold values in the model runs for a comparison with the threshold values derived in this project.
d. better availability of *in situ* validation data, including vertical profiles, and Ferrybox data;

e. combine all available monitoring platforms, including satellite observations. In this way, the strengths and weaknesses of one platform can be compensated by another in terms of spatial and temporal resolution, sampling depth, ability to measure different variables, analytical precision and costs;
f. further subdivision of the newly proposed assessment areas along national boundaries and within countries, following a nested approach;
g. consider the use of variable threshold values versus a single mean assessment value for assessment areas in relation to the assessment of the extent of the area that is not subject to eutrophication and determine its evolution in time;
h. by the ICES data centre: further development of the HEAT tool for OSPAR.

Longer term recommendations are:

i. reconsider the ‘fixed’ 50% deviation from reference chlorophyll concentrations. Some areas may be more sensitive to eutrophication, other areas may be more robust;
j. rethink the current monitoring programs. This could include the repositioning of monitoring stations to match the new assessment areas and ensure sufficient *in situ* data where the number of reliable satellite data is critically low. Options for integrating eutrophication monitoring with other (monitoring) activities and the application of Ferrybox should be explored to reduce costs;
k. agree on joint/coordinated retrieval of satellite data and quality control using the JMP EUNOSAT approach;
l. develop a common protocol for sampling and sample analysis to improve the reliability of the data and quality of the end result. Elements of such a protocol are described in the Activity 3 report;
m. collaboration between North Sea countries to populate a database of ‘match ups’, *ie*. *in situ* samples taken in a window of two hours of satellite overpass under clear sky conditions.
n. develop a scientifically sound procedure to feed data collected with different methods into one common indicator (chlorophyll a);
o. keep an open eye for developments in algorithms, especially for optically complex areas, and high-resolution sensors such as Sentinel-2/MSI for observation of the first nautical mile of coastal waters relevant for WFD monitoring. Data distribution centers such as CMEMS and ODESA online provide analysis-ready validated ocean colour products.

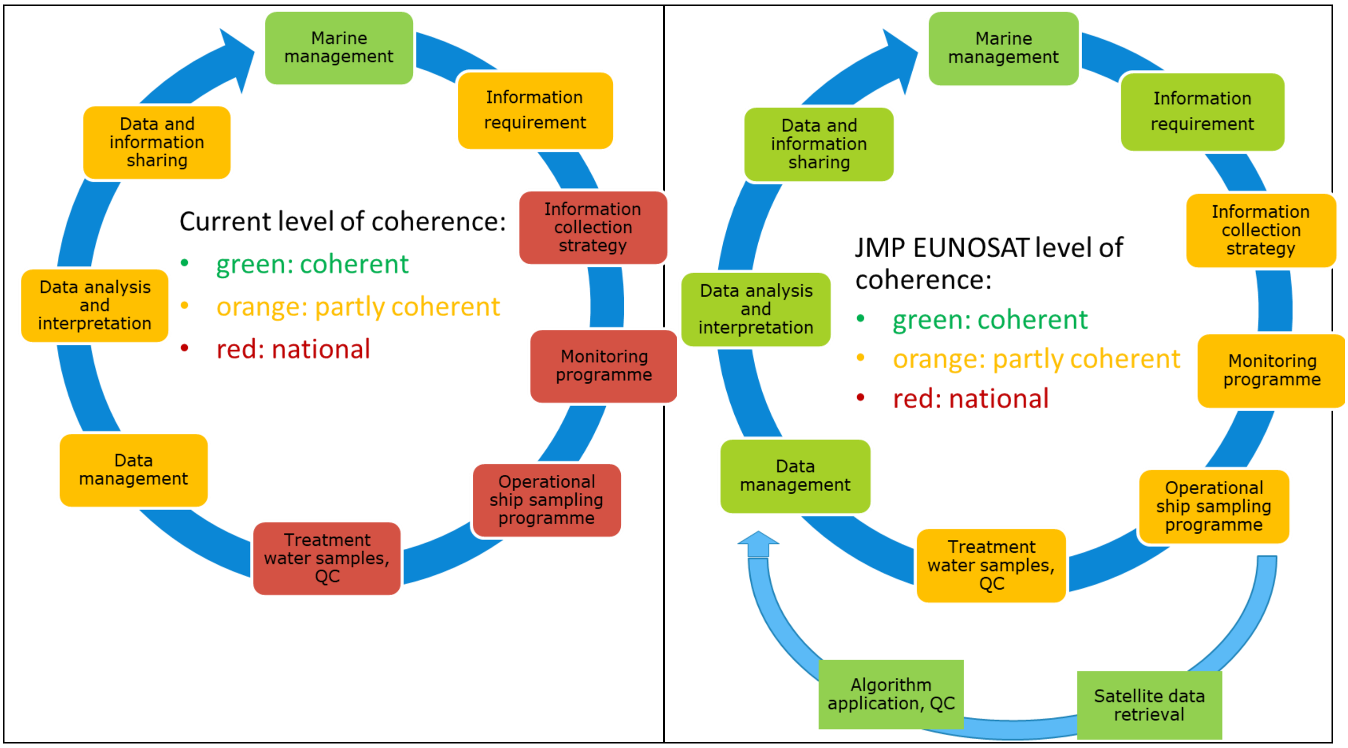

Figure 14. The JMP EUNOSAT project has addressed all steps in the information cycle and proposes options to improve coherence. The left panel shows the current level of coherence among North Sea countries with regard to in situ monitoring and assessment of chlorophyll. The right panel estimates the situation in the (near) future where all JMP EUNOSAT recommendations have been implemented. It also shows the added value of satellite observations (lowest parallel cycle), which are coherent by nature.

7. References

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